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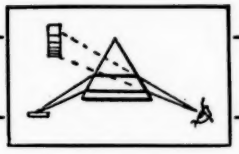

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For further information concerning the Optical Society of America address the Secretary, Dr. L. B. Tuckerman, National Bureau of Standards, Washington, D. C.

Journal of the
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VOLUME 27 JUNE, 1937 NUMBER 6

The Scattering of Light by Water

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(Received April 10, 1937)

By means of a quartz spectrograph and recording densitometer measurements were made throughout the spectral region from 5790 to 2536A of the relative intensities of light scattered by pure water. The scattering coefficient was found to increase with decreasing wave-length in fair agreement with the $\lambda^{-4}f(\mu)$ expression of the density fluctuation theory.

THE absorption coefficient β of a medium for monochromatic light is defined by

$$i=i_0e^{-\beta x}, \quad (1)$$

where i_0 is the original intensity of the light and i the intensity after passing through x cm of the medium. For a liquid in which there is no true absorption β may be regarded as due to scattering of the light by the density fluctuations of the liquid according to the theory of Einstein[1] and Smoluchowski.[2] In this case β is given by

$$\beta=(8\pi^3/27)(\sigma RT/N\lambda^4)(\mu^2-1)^2(\mu^2+2)^2, \quad (2)$$

where μ is the refractive index, λ is the wave-length of the light, $R=8.315\times10^7$ erg deg.$^{-1}$ mole^{-1} is the gas constant per gram molecule, $N=6.06\times10^{23}$ is the Avogadro number per gram molecule, $\sigma=4.95\times10^{-11}$ cm^2 dyne^{-1} is the isothermal compressibility and T is the absolute temperature.

The fraction of light scattered at right angles to the beam is αi, where

$$\alpha=(\pi^2/18)(\sigma RT/N\lambda^4)(\mu^2-1)^2(\mu^2+2)^2. \quad (3)$$

[1] Einstein, Ann. d. Physik **33**, 1275 (1910).
[2] Smoluchowski, Ann. d. Physik **25**, 205 (1908).

TABLE I. *Theoretical scattering coefficient of water.*

λ	α	λ	α
600$\mu\mu$	0.79×10^{-7}	400$\mu\mu$	4.06×10^{-7}
550	1.03	350	7.15
500	1.66	300	14.8
450	2.53	250	34.4

The values of α for water calculated from (3) for a temperature of 295°K are plotted in the smooth curve of Fig. 2 and are given in Table I. (2) and (3) were derived on the assumption of isotropic molecules. For anistropic molecules the formulae require a correction factor[3] greater than unity related to the imperfection of polarization of the light scattered at right angles. A few measurements[3] on water in the visible spectrum indicated that the correction was less than 30 percent; its value in the ultraviolet is not known.

Water has long been known to possess true absorption for wave-lengths longer than 5000A and to be very transparent for shorter wave-lengths. Early measurements by Aufsess[4] of the

[3] Cabannes, Ann. de physique **15**, 1 (1920); Krishnan, Phil. Mag. **50**, 697 (1925).
[4] Aufsess, Ann. d. Physik **13**, 678 (1904).

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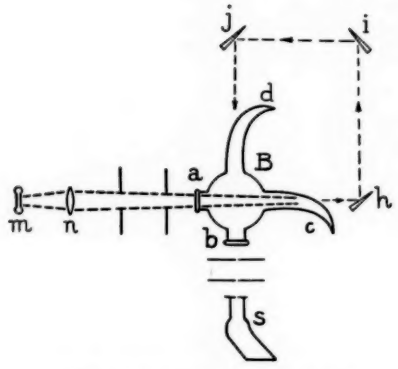

FIG. 1. Light scattering apparatus.

absorption of water at 522$\mu\mu$ and 494$\mu\mu$ appeared to yield values of the absorption in agreement with (2). However, it was pointed out[5] that Aufsess had not completely corrected for reflection from the end plates of the tube of water, and that when this was done the effect was to increase the experimental values about 8 times which removed them considerably from the theoretical scattering values. A recent careful investigation[6] from 366 to 200$\mu\mu$ gave absorption coefficients from 10 to 20 times those calculated from (2).

Since the density fluctuation theory appeared to account for less than 10 percent of the observed absorption of pure water even in the spectral region where water is fairly transparent, it seemed of interest to examine the scattering formula (3). In the case of the absolute value of the scattering of visible light by water Raman and Rao[7] compared the scattering of white light by pure dust free water to that by air and found a ratio 158. This agreed well with the theoretical ratio which from (3) was 140. It was considered that the difference could reasonably be attributed to a small proportion of motes in the water or to the anistropy of the water molecules.

As a further test of (3) the relative scattering coefficients of pure water have been measured from 5790 to 5436A. The apparatus is shown in Fig. 1. The light from a high intensity quartz mercury arc m was focused by lens n into the scattering bulb B. B was of quartz, 10 cm in diameter, with plane quartz windows a and b opposite which were two horns c and d. The beam of light from n was diaphragmed so that it passed through a and into horn c without touching the sides of the bulb. Light scattered from the beam passed out through b to the quartz spectrograph s, diaphragms being placed to prevent the spectrograph from "seeing" any part of the bulb except the dark background provided by horn d.

The bulb was rinsed with distilled water and finally filled by slow evaporation and allowed to stand for several weeks. The water was nearly free from visible motes. Spectra of the scattered light required an exposure of five hours, 2536A being the shortest wave-length which appeared with measurable intensity.

Six comparison spectra were impressed on the same plate with each scattered spectrum. To obtain these the bulb B was removed and the beam of light from lens n was reflected successively by the front surfaces of three quartz wedges h, i, and j; from j the light entered the spectrograph. By means of wire absorbing screens over n six comparison spectra were taken with the same time of exposure on each plate of intensities 100 (i.e., no screen), 58, 37, 22, 10 and 4 percent. The triple reflection from quartz and the increased length of path weakened the light to an order of 10^{-6} so that the exposure for each comparison spectrum was about one hour, which was not too greatly different from that of the scattered spectrum. Therefore it was justified to assume the validity of the reciprocity law of photographic exposure. Curves of each spectrum were made with the recording densitometer from which, omitting obvious and tedious details, the values of the intensities i_s of the scattered spec-

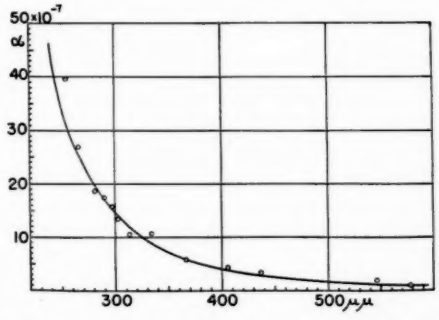

FIG. 2. Scattering coefficient of water, curve theoretical, points experimental.

[5] Martin, J. Phys. Chem. **26**, 471 (1922).
[6] Dawson and Hulburt, J. O. S. A. **24**, 175 (1934).
[7] Raman, *Molecular Diffraction of Light* (1922), p. 49.

trum lines were determined relative to the spectrum lines three times reflected from quartz.

The angle of incidence of the beam of light on each of the quartz surfaces h, i, and j was about 45°. The reflecting powers r throughout the spectral region from 2400 to 6000A were calculated by Fresnel's equations from the average refractive indices of quartz for the ordinary and extraordinary rays. Therefore $i_s r^3$ gave the intensities of the scattered spectrum lines relative to the lines of the direct beam. Corrections were negligible due to the absorption of the light in the relatively small thickness of water in the bulb.

The values of $i_s r^3$ for the various mercury lines were obtained from four plates. At the same wave-length individual values from the respective plates agreed within 25 percent, and their average was probably correct to less than 15 percent. The average values, being in arbitrary units, were multiplied by a constant factor to make them fall closely along the theoretical curve. They are plotted in Fig. 2 and agree with the theoretical curve within the error of experiment.

It is concluded that the observed variation of the scattering coefficient of water with wave-length from 5790 to 2536A is in accord with Eq. (3) of the density fluctuation theory.

Notice of Denver Meetings

A notable physics program is being arranged for the summer meeting of the American Association for the Advancement of Science in Denver, Colorado, June 21–26. This is in keeping with the special nature of this 100th meeting of the Association. The physics portion of the program will be held the latter part of the week to avoid conflict with the eastern meeting of the American Physical Society. Several organizations are planning to take part. The regular Pacific Coast meeting of the American Physical Society will form the nucleus of the program. As usual, some of its sessions will be held jointly with the Astronomical Society of the Pacific. The tentative schedule follows:

Friday, June 25
MORNING: Joint meeting American Physical Society and Astronomical Society of the Pacific.
Symposium on Solar Radiation and Radio Reception.
AFTERNOON: Reserved for excursions.
Saturday, June 26
MORNING: Joint session with Section B; American Association for the Advancement of Science.
Symposium on Cosmic Physics.
AFTERNOON: Contributed papers.

The Symposium on Cosmic Physics will be opened with a brief talk on the newly completed high altitude laboratory on Mt. Evans. Dr. J. C. Stearns of the University of Denver, who has been closely concerned with the design and construction of this laboratory, will speak about its features and purposes. Among the invited papers will be the following:

Further Experiments with the Geomagnetic Cosmic-Ray Effects and Their Bearing upon the Nature and Energy Distribution of the Primary Cosmic Radiation. THOMAS H. JOHNSON, *Bartol Research Foundation.*
The Importance of Observations from the Upper Atmosphere in Long Range Weather Forecasting. HURD C. WILLETT, *Massachusetts Institute of Technology.*
Nature of the Penetrating Cosmic Ray. J. C. STREET, *Harvard University.*

The American Association of Physics Teachers will hold a meeting on Thursday, June 24, with the morning session devoted to contributed papers and in the afternoon a symposium of invited papers on the Training of High School Physics Teachers.

Optics in the Large*

M. HERZBERGER
Kodak Research Laboratories, Rochester, New York
(Received April 7, 1937)

The introduction of the natural and the diapoint variables has simplified considerably the investigation of problems in the large, problems where we can give the eiconal in closed form, and therefore for each object ray the image ray. The author and H. Boegehold have, first together and then alone, investigated problems of this kind. The author sketches first once more his new method, and gives then a series of examples, such as the eiconal for the case where to each object point belongs a rotation symmetric caustic, the eiconal for sharp image formation of two surfaces, the eiconal in the case where there is perfect centric symmetry, and other examples which are discussed as far as the time limit permits.

IF we investigate the image of a point, there are four possibilities: (a) The rays coming from a point form, according to the law of Malus, a system or bundle of rays which is normal to a series of surfaces, the so-called wave surfaces, and we know that these rays are tangential to two surfaces, the two caustic surfaces, which, in general, have very interesting connections with each other, investigated particularly by W. R. Hamilton and Allvar Gullstrand. Both caustic surfaces are, within certain limits, arbitrary. They are met in geodetic lines by our rays, and there is, in general, only a finite number of points where the two surfaces intersect each other such that the ray is a tangent common to both; these special rays are those which Hamilton called principal rays, along which there is no astigmatism, as we are accustomed to say in optics, or as the geometricians say, the corresponding wave surfaces have an umbilic point.

(b) Let us assume a symmetry plane through the object point. Then the two caustic surfaces can be easily distinguished from each other. One, which we shall call the primary surface, is a surface having the plane as symmetry plane, whereas the secondary caustic surface is formed of a part of the plane. The secondary focus on each ray is the point where the ray crosses the symmetry plane. The secondary foci form a two-dimensional manifold of points in the symmetry plane.

(c) The bundle has an axis of symmetry. In this case, we can demonstrate that the primary caustic surface is rotation symmetric around the symmetry axis; all rays cross the symmetry axis and their crossing points form the secondary foci, so that the secondary caustic consists only of points on the symmetry axis. The symmetry axis itself is, of course, a principal axis without astigmatism.

(d) The image bundle unites in a point. In this case, every ray is a principal ray, anastigmatic, and the two caustic surfaces degenerate into the image point.

Let us now restrict our attention to rotation symmetric optical systems. Here it is fortunate that the first types of caustics do not occur. If we consider a finite or infinite object point, the plane through it and the axis will always be a symmetry plane for optical image formation; thus, for an arbitrary point, only (b), (c), and (d) are possible. If we consider particularly a point on the axis, the latter will form a symmetry axis and only (c) and (d) will be possible.

Now, it is a very interesting and valuable problem to investigate, for a given optical system, whether there are points which have a sharp image according to (d), and if so, whether these points form any surfaces, such that we can say we have surfaces sharply imaged with the help of the system. If we do not want to aim too high, we can ask whether there is at least a surface which gives an image as good as the axis point, that means, one which gives to each of its points a rotation symmetric image caustic.

By "problems in the large" we mean problems of the following kind: The investigation of systems with a certain kind of image formation, e.g.,

* Communication No. 617 from the Kodak Research Laboratories.

the investigation of systems which give a sharp image formation of the whole space, systems which give to each point a rotation symmetric caustic, etc. From these conditions, we shall study the special qualities of the image formation. We are able to do this because of the pioneer work of W. R. Hamilton[1] and later, Bruns.[2]

A ray is given, if the coordinates x, y, and z of one of its points are known, and its direction cosines ξ, η, $\zeta=[1-(\xi^2+\eta^2)]^{\frac{1}{2}}$. Hamilton showed that, for each optical system, there exist three functions:

$$\begin{aligned} V(x, y, z;&\quad x', y', z')\\ W(x, y, z;&\quad \xi', \eta', \zeta')\\ T(\xi, \eta, \zeta;&\quad \xi', \eta', \zeta') \end{aligned} \tag{1}$$

such that we can find the missing coordinates by simply differentiating our functions, so that, for instance,

$$\begin{aligned} n\xi &= -V_x, & n'\xi' &= +V_x,\\ n\eta &= -V_y, & n'\eta' &= +V_y,\\ n\zeta &= -V_z, & n'\zeta' &= +V_z, \end{aligned} \tag{2}$$

since ξ, η, ζ; ξ', η', ζ' are connected, respectively, by

$$\xi^2+\eta^2+\zeta^2=\xi'^2+\eta'^2+\zeta'^2=1. \tag{3}$$

We have to norm W and T, either by eliminating ζ and ζ' by using (3) or, by using (3), to make W or T a homogeneous function of well-defined order in the direction cosines. The differentiation of W and T, taking these side considerations into account, gives rise to formulae, which are only a little more complicated, and which again allow the immediate determination of the position of object and image ray for each choice of the coordinates. Hamilton's very ingenious work was not understood by his contemporaries and his conception of the characteristic function was rediscovered in 1895, with a slight change, by the German astronomer Bruns.

Let us consider V, W, and T as functions of four variables, e.g.,

$$\begin{aligned} V(x, y,&\quad x', y')\\ W(x, y,&\quad \xi', \eta')\\ T(\xi, \eta,&\quad \xi', \eta') \end{aligned} \tag{4}$$

where we can, for instance, take x, y, x', y', as the coordinates of a plane surface in object and image space which the ray crosses, especially the coordinate planes $z=0, z'=0$. Then, V, W, and T have simple geometrical meanings and we get

$$\begin{aligned} n\xi &= -V_x & n\xi &= W_x & nx &= T_\xi\\ n\eta &= -V_y & n\eta &= W_y & ny &= T_\eta\\ & \text{or} & & \text{or} & & \\ n'\xi' &= V_{x'} & n'\xi' &= W_{\xi'} & n'x' &= -T_{\xi'}\\ n'\eta' &= V_{y'} & n'\eta' &= W_{\eta'} & n'y' &= -T_{\eta'}. \end{aligned} \tag{5}$$

Why is that sufficient to determine the image formation of an optical system? The manifold of the rays is four-dimensional. Four parameters are therefore sufficient to determine the rays. What is more important, however, is that V, W, and T are the general functions of their arguments, so that we can say: Every function V, W, and T, which we choose, determines for us a certain image formation. Only we must demand that a certain functional determinant:

$$\begin{aligned} V_{xx'}V_{yy'}-V_{xy'}V_{yx'} &\neq 0\\ W_{x\xi'}W_{y\eta'}-W_{x\eta'}W_{y\xi'} &\neq 0\\ T_{\xi\xi'}T_{\eta\eta'}-T_{\xi\eta'}T_{\eta\xi'} &\neq 0 \end{aligned} \tag{6}$$

does not vanish, because that guarantees that the above equations determine x', y', ξ', η' as functions of x, y, ξ, η; that means they determine for each object ray an image ray and *vice versa*.

Bruns was the first to attack problems in the large. As an example, let us assume that W is linear in two of its variables, e.g., ξ' and η'. We have

$$W=f(xy)\xi'+g(xy)\eta'+h(xy). \tag{7}$$

Formula (5) gives

$$n'x'=f(xy), \qquad n'y'=g(xy). \tag{8}$$

We see that the characteristic (7) gives an image formation such that the coordinate planes are sharply imaged upon each other.

Another example from Bruns:

$$W=f(\xi', \eta')x+g(\xi', \eta')y+h(\xi', \eta'). \tag{9}$$

Eq. (5) shows that for this characteristic function:

$$n\xi=f(\xi', \eta'), \qquad n\eta=g(\xi', \eta'), \tag{10}$$

which means that (10) is the characteristic function for a telescopic system or a prism system in

[1] W. R. Hamilton, third supplement to an essay on the theory of systems of rays. Trans. Irish Academy **17**, 1–144 (1837); also in *Mathematical Papers*, Vol. I (1931).

[2] H. Bruns, "Das Eikonal," Leipzig Sitz. ber. **21**, 321–436 (1895).

which to each parallel bundle corresponds a parallel bundle where the image planes are imaged upon each other.

If we consider V as linear, for instance, in x and y

$$V=f(x'y')x+g(x'y')y+h(x'y'). \qquad (11)$$

We obtain according to (5):

$$n\xi=-f(x', y'), \qquad n\eta=-g(x', y'). \qquad (12)$$

We see that to each parallel bundle corresponds a point of the image plane, as in an ideal photographic objective.

Since this work of Bruns, we know that the concept of an ideal photographic objective, an ideal telescopic objective, and an ideal microscope is no Utopian idea, but we know also since his investigations that the problem of giving a sharp image of the whole space, as the so-called theory of collinear optics suggests, is Utopian and cannot be approached.

The problem of giving a sharp image of space leads to the characteristic, by suitable choice of the coordinate axis:

$$W=n(x\xi'+y\eta'). \qquad (13)$$

Eq. (5) shows that in this case we have

$$\begin{aligned} \xi&=\xi', \qquad nx=n'x', \\ \eta&=\eta', \qquad ny=n'y'. \end{aligned} \qquad (14)$$

That means, an image formation in which (disregarding an eventual rotation of the whole space) object and image ray are parallel and the magnification is constant for the whole space and equal to the ratio of the respective refractive indices.

This is the point from which H. Boegehold and I started our work in this direction, but we made a restriction. We nearly always investigated only rotation symmetric systems, since these are of the greatest practical interest. Hamilton showed that for the angle characteristic we can take as variables:

$$\xi^2+\eta^2, \quad 2(\xi\xi'+\eta\eta'), \quad \xi'^2+\eta'^2. \qquad (15)$$

In the case of the other characteristics, Bruns first used the other combinations, for instance,

$$x^2+y^2, \quad 2(xx'+yy'), \quad x'^2+y'^2. \qquad (16)$$

We first investigated the image of a plane. For this purpose, the mixed characteristic V is especially apt, because it gives x' and y' as functions of x, y, ξ', η', so that we can easily calculate the caustics corresponding to a certain point x, y of the object plane.

We gave[3] in closed form the characteristic for the case of the object plane being sharply imaged on a curved surface or on a plane.

Here an interesting function began to play a certain role which later on was called diamagnification. If, from object and image point, we drop perpendiculars to the axis, the diamagnification is equal to the ratio of these perpendiculars. If we assume that this magnification is constant all over the surface, we get particularly simple laws and specially interesting image formations. If that is the case for the image of a plane on a plane, we say the image is free from distortion; in the more general case, we coin the word "distant true."

Then, we investigated the case in which to each point of our plane belongs a rotation symmetric caustic. Here again, we had a surprise, which pointed to further developments. We knew that in the neighborhood of the axis, a special condition must be fulfilled to guarantee that the neighborhood caustics remain rotation symmetric, namely, the so-called Staeble-Lihotzky condition, or isoplanatic condition, one of the most important tools of the optical designer. First I believed, together with Lihotzky, that such a condition must be fulfilled outside the axis too, in order to guarantee symmetry of the caustics, but that proved erroneous. Now, we asked, what would fulfillment of such a condition outside of the axis mean? Here we found that fulfillment of this condition—homoplanatic image formation, as we called it—guarantees that the caustic keeps its form throughout the field. Thus, we gained definite information which gives us control of the deformation of the caustics, if we go from one point to another, and, moreover, we found a new kind of image formation with specially simple qualities.

But, we were not content with investigating the image of a simple plane. We wanted to have the same laws for the image formation of a

[3] M. Herzberger, *Strahlenoptik* (J. Springer, 1931), pp. 167–175.

curved surface, and especially to see if more than one surface, and eventually the whole space, could have a fairly good image formation, or, at least, an image formation which fulfills certain conditions.

Here the mixed characteristic is no longer usable, because solution of the calculations necessary would require a genius like Hamilton. Hence, we used the angle characteristic T. We regretted this, however, since the angle characteristic cannot be used for telescopic systems and we knew from the work of Bruns that telescopic systems sometimes have particularly interesting qualities. The discovery of the duality principle[4] in 1934, which allows us to obtain the laws in telescopic systems by transferring laws of other systems, proved a satisfactory consolation.

The logic of science would have asked that here we make the invention of the natural variables, published in last year's *Journal of the Optical Society*,[5] but, since we did not, we had to carry out a great amount of calculations. However, in this survey, I may be allowed to introduce the new variables here. We can introduce as variables instead of those used in (15):

$$\kappa=\zeta, \quad \nu=\xi\xi'+\eta\eta'+\zeta\zeta', \quad \mu=\zeta'. \tag{17}$$

If we do so, the derivatives of the characteristic T have a very significant meaning.

If we coordinate to a point its secondary focal point, we have a one-to-one correspondence between the points of each object and image ray. For each pair of such points, we have a certain number, namely, the ratio of the perpendiculars on the axis, which we call diamagnification.

Now, this coordination of the points follows the same laws as Gaussian optics. If diamagnification 1 determines the cardinal points, diamagnification n'/n determines the nodal points; if we call focal points the points belonging to the infinite object and image points, then we can define focal length as in Gaussian optics and get:

$$n'f+nf'=0. \tag{18}$$

We can show particularly that, for each pair of rays, there exists a pair of axis points, called central points, such that the vectors from central points to coordinated points are parallel. The central points are the perspective centers of our coordinations.

Now, if we introduce these variables κ, λ, μ they determine a ray. Then T_κ becomes nothing else than nz, where z is the distance of the central point from the origin; T_μ becomes $=-n'z'$, where z' is the distance of the image central point, and we have

$$T_\lambda=nf'=-n'f, \tag{19}$$

where f is the focal length along the ray. Important is the fact that a transformation of coordinate origins means only an additional function linear in λ and μ, so that especially T_λ and all the second and higher derivatives of T are magnitudes which have only to do with the system and are independent of the accidentally chosen origins.

With the help of these variables, we can now investigate the problems which Boegehold and I attacked.

I. Centric Symmetric Systems

For systems[6] with a kind of centric symmetry, for instance the systems consisting of concentric leaves, we obtained, if we put our origins into the center, the equations:

$$T=f(\lambda). \tag{20}$$

T must be an arbitrary function of λ alone.

Here, to each point corresponds a rotation symmetric caustic, since the connection line point-center is always a symmetry axis. If we require that, besides the center, another point shall be sharply imaged, we get either the system of Bruns, which images the whole space sharply or

$$T=R[(\beta^2+1/\beta)-2\lambda]^{\frac{1}{2}}$$
$$=R\left[\frac{(\beta\xi'-\xi)^2+(\beta\eta'-\eta)^2+(\beta\zeta'-\zeta)^2}{\beta}\right]^{\frac{1}{2}}. \tag{21}$$

This characteristic function gives an image formation which gives a sharp image of two concentric spheres, one with the magnification $n\beta/n'$, the other with a magnification $n/n'\beta$. For concentric systems, Boegehold and I succeeded in

[4] See for instance M. Herzberger, "On the Fundamental Optical Invariant," J. O. S. A. **25**, 295–304 (1935).

[5] M. Herzberger, "New Theory of Optical Image Formation," J. O. S. A. **26**, 197–204 (1936).

[6] H. Boegehold and M. Herzberger, "Kugelsymmetrische Systeme," Zeits. für Ang. Math. u. Mech. **15**, 157–178 (1935).

giving all possible practical examples for such an image formation; and I succeeded the last time in giving the angle characteristic in closed form, for any concentric system.

II. Systems with Two Sharply Imaged Surfaces

Eq. (21) gives an example of such an image formation. Both object and image surfaces are spheres. The question is: Are there other such image formations? Maxwell[7] denied this possibility but we found[8] an affirmative answer. The characteristic in this case is shown by:

$$T=R\left[\frac{(\beta\xi'-\xi)^2+(\beta\eta'-\eta)^2+\dfrac{1-\beta^2}{1-\alpha^2}(\alpha\zeta'-\zeta)^2}{\beta}\right]^{\frac{1}{2}}. \tag{22}$$

We see in this case that both surfaces are quadrics; the first object surface is similar to the second image surface, the second object surface to the first image surface, and the similarity coefficient is equal to the ratio of the refractive indices.

The first object and image surface are affine to each other, the lateral magnification being equal to $(n/n')\beta$, the axial magnification being equal to $(n/n')\alpha$. The second object and image surface are affine to each other, the lateral magnification being $n/n'\beta$, the axial magnification, $n/n'\alpha$. For $\alpha=\beta$, (22) goes over into (21), and the quadrics degenerate into spheres. The error of Maxwell is understandable. He had demonstrated that the configuration consisting of first and second object surfaces must be similar to the configuration consisting of first and second image surfaces with the ratio of the refractive indices as similarity coefficient. But, he concluded further that, in this case, object and image surfaces must be similar, overlooking the possibility that first object and second image surfaces, first image and second object surfaces might be similar.

[7] C. Maxwell, On the general laws of optical instruments, *Scientific Papers I* (1858), pp. 271–285.

[8] H. Boegehold and M. Herzberger, "Kann man zwei verschiedene optische Flächen scharf abbilden?" Comp. Math. **1**, 1–29 (1935).

III. Spatial Symmetric Systems

The centric systems give to each object point a symmetric image caustic. Let us ask now whether there are any other image formations with the same quality. If we call a rotation symmetric caustic, a caustic rotation symmetric around a straight line, the answer is in the negative; if we allow a curved line as axis, the answer is in the affirmative. H. Boegehold[9] investigated these systems and found the characteristic which can be written:

$$T=R(1-\lambda-\tilde{\mu}\tilde{\kappa}/C)^{\frac{1}{2}}, \tag{23}$$

where
$$\tilde{\kappa}=C\kappa+[C(C+2)]^{\frac{1}{2}},$$
$$\tilde{\mu}=C\mu+[C(C+2)]^{\frac{1}{2}}.$$

The image caustics are symmetric around elliptic curves, lying in the meridian plane and going through the center of the image formation. And what is right for the object points is right for the points of the image space, too. All rays from an image point are in the object space symmetric around an ellipse in the meridian plane going through the center.

Conclusion

The aim of all these investigations can be stated as follows: If we are to investigate the image errors of optical systems with finite aperture and field, we must understand more about the possibilities of image formation; we must have a skeleton of well-known and well-studied image formations possible according to the laws of optics. The deviation from these well-known image formations might then be regarded as image errors. On the other hand, the combination of variables in these special image formations leads to the knowledge of optical invariants like sine condition, Petzval condition, etc.

Image theory in the large is a problem only superficially attacked heretofore. The investigations in the large, which, besides their importance, have their own charm and beauty, will pave the way towards a deeper understanding of the problems stated above.

[9] H. Boegehold, "Raumsymmetrische Abbildung," Zeits. f. Instrumentenk. **56**, 98–109 (1936).

Colorimetry: Preliminary Draft of a Report on Nomenclature and Definitions*

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Committee on Colorimetry
(Received March 26, 1937)

IT seems desirable at this time to acquaint the members of the Society and others interested in this subject with certain aspects of the work which this committee has been doing in connection with the preparation of a report on the subject of color and colorimetry.

In the early discussions on the type of report which this committee should prepare, it was decided that the report should be a comprehensive treatment not restricted entirely to colorimetrics, but including a treatment of various phases of the larger problem of color, particularly those phases which have an important bearing on the metrical aspects of the problem. In order to prepare such a report it is necessary, of course, to discuss at considerable length subjects lying within very diverse fields of both objective and subjective sciences. It appears very desirable, in order to treat the subject clearly and without ambiguity, that a great deal of attention be paid to the preparation of a series of harmonious definitions and a logical and nonambiguous nomenclature.

It is a relatively simple matter to deal with the problem of nomenclature and terminology where the subject matter is restricted to a somewhat narrow field. For instance, if interest is confined, let us say, to the field of radiometry, it is not particularly difficult to establish a series of terms and definitions within which there is little conflict or lack of logical interrelationships. When, however, the treatment must be extended to cover not only radiometry but also the psychophysical and psychical aspects of photometry and colorimetry, the task becomes very much more complicated. In any one of these fields there is already established a fairly satisfactory series of terms and definitions for use in the discussion of the subject both qualitatively and quantitatively. But when an attempt is made to discuss within a single treatment all of these phases, immediately great difficulty is encountered and confusion arises due to the frequent usage of the same word in different senses and to the lack of logical correlation between analogous terms.

Quite early in the preparation of this report it became apparent that the material to be dealt with could be logically separated into three rather distinct categories. These categories may be designated as physical, psychophysical, and psychical, and in many cases a quantity belonging to one of these categories has its direct correlate in the other two. In 1925 the O. S. A. Committee on Spectrophotometry published a report[1] in which was presented a table containing several very pertinent suggestions for harmonizing the nomenclature of greatest importance in the field of radiometry and photometry. In fact, this may be considered as the starting point from which this committee has attempted to proceed in an effort to extend the scope of the nomenclature to include colorimetry and to further simplify and systematize the material. Some of the suggestions which were advanced at that time rather tentatively and with a certain degree of timidity, the present committee wishes now to urge be adopted for general usage, and, in addition to these, certain other recommendations are being made which we feel, if adopted, will tend emphatically to promote simplicity and rationality in the terminology of these fields.

Needless to say, very serious consideration has been given to this subject and lengthy discussions

* This draft has been prepared by the chairman of the committee and copies were submitted to all members some weeks ago. Criticisms from some members have been received, but the draft as a whole has not received the final and official approval of the entire committee. Many of the items as indicated have received the approval of the entire committee. The chairman in preparing this draft has attempted to present what he believes to be the consensus of the committee's opinion, but it is possible that in some cases his statements are tinged to some extent by his own personal opinion.

† Chairman of the O.S.A. Committee on Colorimetry. The personnel of this committee is: E. Q. Adams, C. Bittinger, E. C. Crittenden, C. Z. Draves, J. W. Forrest, C. E. Foss, H. P. Gage, K. S. Gibson, I. H. Godlove, A. C. Hardy, D. B. Judd, E. M. Lowry, M. Luckiesh, D. L. MacAdam, Dorothy Nickerson, B. O'Brien, M. R. Paul, Louise L. Sloan, W. T. Spry and W. B. VanArsdel.

[1] J. Opt. Soc. Am. and Rev. Sci. Inst. **10**, 169 (1925). The Progress Committee on Spectrophotometry for 1922–23 consisted of the following members: K. S. Gibson, chairman, H. P. Gage, C. E. Keuffel, A. H. Pfund and A. G. Worthing.

have occurred within the personnel of the present committee and it must be admitted that complete unanimity of the committee on this has not been obtained. However, after the matter had received thorough discussion the various proposals were submitted to the committee for ballot and, with the exception of one or two cases, a large majority affirmative vote was given. In the following paragraphs we wish to present this suggested nomenclature with some discussion in support of its adoption.

In Table I is presented the proposed nomenclature. The various terms are designated by numbers (in parentheses) for reference.

In the 1922 report of the Committee on Colorimetry it was urged that the term *radiation* (1) be used in referring to the *process* and not as synonymous with *radiant energy*. The present committee wishes to emphasize this recommendation strongly and to urge that this term be restricted to use when referring to the *process* by which *radiant energy* is generated. Furthermore, it seems desirable to apply the same principle to several other terms, such as *propagation*, *transmission*, *reflection*, *irradiation*, *absorption*, *emission*, etc.

Terms (2), (3), (4), and (5) seem to need little discussion since there is fairly unanimous agreement on their usage and definition. Some criticism has been made of the term *radiant density* which is defined as referring to the volume density of radiant energy. Most of this criticism is to the effect that such a term is not needed, but since it is used to some extent, at least in the field of radiometry, it does not seem unwise to include it. It has been suggested that the term should be *radiant energy density*. On this basis we might argue that term (5) should be *radiant energy flux*. It seems quite unnecessary in terms (4), (5), (6), and (7) to include the word "energy." It should be realized readily that in all these cases the word "radiant" is synonymous with "radiant energy." We suggest *radiant density* then as a synonym for the phrase "volume density of radiant energy," just as *radiant flux* is a synonym for the phrase "time rate of flow of radiant energy" or "flux of radiant energy."

Some rather severe criticism has been leveled at the term *radiant emittance* (6). However, the term seems to us to be extremely meaningful and almost self-defining. We realize fully that its dimensions, as indicated by the defining equation, dP/da, are radically different from other terms having the "ance" ending, such, for instance, as *reflectance*, *transmittance*, etc., these latter terms

TABLE I. *Radiometric vs. photometric nomenclature and units.*

Radiometric				Photometric		
A	*B*	*C*		*A*	*B*	*C*
(1) Radiation				(10) Lumination (Illumination)		
(2) Radiator				(11) Luminator		
(3) Radiant energy	U	erg, joule		(12) Luminous energy	Q	(20) Lucifer (21) Lumerg (22) Talbot
(4) Radiant density	$u=dU/dv$	erg/cm³		(13) Luminous density	$q=dQ/dv$	lumerg/cm³
(5) Radiant flux	$P=dU/dt$	erg/sec or watt		(14) Luminous flux	$F=dQ/dt$	lumerg/sec or lumen
(6) Radiant emittance	$W=dP/da$	watt/cm²		(15) Luminous emittance	$L=dF/da$	lumen/cm²
(7) Radiant intensity	$J=dP/d\omega$	watt/ω		(16) Luminous intensity	$I=dF/d\omega$	lumen/ω
(8) Radiance	$N=\dfrac{dP}{d\omega da\cos\theta}$	$\dfrac{\text{watt}/\omega}{\text{cm}^2}$		(17) Luminance (Brightness)	$B=\dfrac{dF}{d\omega da\cos\theta}$	$\dfrac{\text{lumen}/\omega}{\text{cm}^2}$
(9) Irradiance	$H=dP/da$	watt/cm²		(18) Illuminance (Illumination)	$E=dF/da$	lumen/cm²

(19) Luminosity (Visibility), K, Luminous efficiency of radiant energy—$K_\lambda=F_\lambda/P_\lambda$—, lumens per watt

B, symbol and defining equation, C, units, v, volume, a, area, ω, solid angle, t, time.

being pure numerics. Considered from an absolutely logical point of view perhaps this is undesirable. We feel, however, that it is impossible to construct a nomenclature which is absolutely logical without introducing so many entirely new words and phrases that the nomenclature becomes practically useless. It seems to us that there is very little likelihood that a nomenclature containing a large number of new words or redefined words has the remotest chance of being adopted generally. We have therefore taken the position that the first qualification of the nomenclature should be simplicity and direct suggestive meaningfulness of the term. The word "emittance" appearing in this term (6) is to be given its most general connotation and not a specific one. The dictionary states that the verb "emit" means to send forth, to draw or give out or off, to cause to issue, etc. The term *radiant emittance*, therefore, directly indicates the giving off of radiant energy by a radiator.

The term *radiance* (8) was proposed by the O. S. A. Committee on Spectrophotometry.[1] Some objection has been made to the use of this term on the grounds that it is used abroad in the same sense as term (15), *luminous emittance*. So far as we are aware, this term has not been used in this country to any extent in any sense, nor has it achieved official recognition or extensive usage abroad as synonymous with luminous emittance. In any case, we feel that such a usage is entirely illogical.

The reader will doubtless realize by this time that all the proposed terms relating to radiant energy are based on the root *radi*, while all of the terms in the photometric column are based upon the root *lumin*. It seems completely illogical to use the term *radiance*, obviously directly analogous to *radiant*, *radiator*, etc., in referring to a psychophysical quantity much more appropriately referred to by a term indicating its membership in a group of *luminous* quantities.

Term (9), *irradiance*, is proposed in lieu of *irradiation* which, again, we strongly urge should be limited to use in referring to a *process*.

As was suggested by the Committee on Spectrophotometry,[1] the term *lumination* is logically analogous to *radiation*, both of these being restricted to use in reference to the *process* and not to a specific quantity.

During recent years a great deal of dissatisfaction has been expressed from many sources with the use of the term *illumination* when defined as a quantity, especially when it must be used in many cases in a nonquantitative sense, as, for instance, "diffuse illumination." As a matter of fact, many writers in the field have attempted to distinguish between the qualitative and quantitative aspects of this term by using such terms as "illumination level," "amount of illumination," "illumination intensity," "illumination value," etc. when referring to the quantitative aspect. This seems to be an extremely undesirable situation, especially when the remedy is so simple. All that is necessary to cure this trouble is to agree that the terms *lumination* and *illumination* shall be used only in referring to the respective processes, namely, the emission of light from an effective source and the incidence of that light on a surface, and, further, to adopt the terms *luminance* (17) and *illuminance* (18) to be used for expressing the quantitative results of these respective processes. Thus *luminance* becomes a substitute for the present term "brightness" and *illuminance* a substitute for "illumination" as now defined quantitatively.

There are many who feel that a serious mistake was made when the word "brightness" was defined in its present sense, that is as a psychophysical quantity, and that it is much more logically used as a name for the intensity attribute of *color*, a purely psychical entity. When the Colorimetry Committee prepared its report in 1922 much careful attention was devoted to the choice of names for the three attributes of color. There was substantial unanimity of opinion on the choice of *hue* and *saturation*. It was felt by that committee and by many others with whom the committee consulted, that the most appropriate word for the name of the third attribute of color was "brightness," but, unfortunately, the term brightness had already been defined and had come into use in the psychophysical sense. The best compromise that could be made, therefore, was to recommend the term "brilliance" as the name of the intensity attribute of color. This term has been criticized most violently ever since the appearance of that report. It has come into usage to some extent, but chiefly by those individuals who are intimately associated with the

field of colorimetry and only to a very slight degree by those outside of this field.

The present committee realizes the seriousness of a proposal to change established nomenclature. It feels, however, that under certain conditions a change of nomenclature, with its inevitable confusion, is to be preferred to the perpetuation of a nomenclature that is manifestly illogical and pernicious. Possibly the good to be derived in future years from an improvement in nomenclature is sufficient to far outweigh the confusion which a change may cause for a little time at present.

It has been suggested by some critics that the term *radiance* should be defined more logically in the sense of term (5), dU/dt, and again by others that it is much more logical to use it in the sense of term (6), dP/da. The recommendation of this committee to define *radiance* as term (8), $dP/d\omega da \cos\theta$, is based largely on the fact that in the group of psychophysical terms (those classified under the heading "Photometric" in Table I) the two which are used probably with the greatest frequency are (17) and (18) and for these it was desirable to obtain single-word terms of maximum suggestive connotation. Since it is extremely desirable, if at all possible, to release the word *brightness* for use to denote one of the attributes of color, a purely psychical quantity, it seems to the committee that the word *luminance* is most appropriate as a name for that which is now defined as brightness. This being the case, it seems most logical to recommend *radiance* as the name for the direct physical correlate of the psychophysical quantity, *luminance*.

It has been urged that the terms "radiant emittance" and "radiance" be interchanged from the usage as recommended in Table I. Such an interchange as we see it has only one virtue: it would make radiance and irradiance quantities having the same dimensions. In the committee's opinion the achievement of this is not as important as obtaining a single meaningful word for use as a name of quantity (17). If the interchange mentioned above were made, the proposed substitute for "brightness" would have to be "luminous emittance" and we feel there is much less likelihood of the acceptance of such a term as a substitute for brightness as at present defined. Again, keeping in mind the extreme desirability of simplicity and meaningfulness, the committee believes that the recommendations made represent the best compromise.

The use of the word *emittance* in conjunction with *luminous* (15), has also been criticized on the same ground as the criticism already mentioned of term (6). The committee's argument for the term *luminous emittance* is naturally the same as for *radiant emittance*, that the phrase is meaningful and almost self-definitive.

Some objection has been raised to term (12), *luminous energy*, on the ground that this psychophysical quantity is not energy. As an alternative the term *lumergy* has been suggested. In considering this, the committee felt that the actual coining of new words is to be avoided if possible. Again, on strictly puristic grounds, the criticism may be justified. Once more we may answer that the term is definitely meaningful and if it be appropriately defined there seems to be little likelihood of any confusion arising as to its character. Thus, if we say that *luminous energy* is *radiant energy* evaluated with respect to its ability to evoke the *brightness* (brilliance) attribute of color, there would seem to be little danger that anyone would think that it is a quantity which can be measured in terms of ergs, particularly when we specifically adopt as a name of the unit in which luminous energy is to

TABLE II. *Results of ballot on nomenclature sent to the members of the Colorimetry Committee, May 1936. 21 ballots sent out, 20 returned.*

		Yes	No
1	Radiation	20	
2	Radiator	20	
3	Radiant energy	20	
4	Radiant density	15	5
5	Radiant flux	20	
6	Radiant emittance	18	2
7	Radiant intensity	20	
8	Radiance	18	2
9	Irradiance (irradiation)	18	2
10	Lumination (illumination)	19	1
11	Luminator	18	2
12	Luminous energy	17	3
13	Luminous density	16	4
14	Luminous flux	20	
15	Luminous emittance	18	2
16	Luminous intensity	20	
17	Luminance (brightness)	17	3
18	Illuminance (illumination)	18	2
19	Luminosity (visibility)	17	2
20	Lucifer	7	10
21	Lumerg	11	9
22	Talbot	16	2

TABLE III.

Process Names	*A*	*B*
Reflection	Reflectance	Reflectivity
Absorption	Absorptance	Absorptivity
Transmission	Transmittance	Transmissivity
Emission	Emittance	Emissivity

be expressed the *lumerg*, the direct psychophysical correlate of the erg.

For many years there has been considerable dissatisfaction with the use of the word "visibility" as at present defined. Its present meaning is an extremely restricted one and the term used extensively in reference to other aspects of visual experience. There has been a marked increase in the sentiment both in this country and abroad to substitute for the word "visibility" as at present defined in the I.E.S. nomenclature, the word "luminosity." This committee feels that such a step is desirable. We therefore propose that the term *luminosity* (19) be defined as the luminous efficiency of radiant energy. This action is in accord with the action reported by Dr. W. E. Forsythe, from which we quote the following:

"It was agreed that the word, *luminosity*, should supersede the word, *visibility*, for expressing the relation between luminous flux and radiant flux. The *luminosity* of a sample of radiant flux is, therefore, defined as the luminous efficiency of that radiant flux and is expressed in lumens per watt." [2]

The committee has considered the possibility of defining the word "light." The consensus of opinion seems to be that it is undesirable to define this term in a quantitative sense, but to define it as a general term for use when it is unnecessary or undesirable to indicate some specific quantitative aspect of visual experience. The definition which seems to be most acceptable is as follows:

Light is radiant energy evaluated with respect to its capacity to evoke the brightness attribute of color.

This definition contains no implication as to whether light quantitatively is proportional to the *rate* at which radiant energy is received by the visual receptors or to the *total amount*. If it should be considered desirable to quantify the definition the committee feels that it should be defined as dependent upon quantity rather than rate. However, again, we wish to repeat the recommendation that no attempt be made to quantify the definition of the word "light."

[2] Rev. Sci. Inst. **7**: 322 (1936).

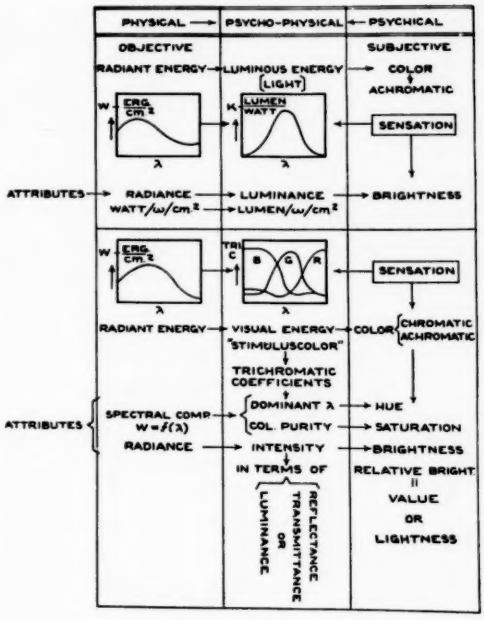

FIG. 1.

However, some of the committee felt that the word, during the evolution of our language, has acquired some more or less disagreeable connotations and hence is unsuitable for the name of this unit. In any case the majority vote was for the *lumerg*.

Referring again to Table I, terms (21) and (22) represent names for units which the committee has voted to adopt. The decision was almost unanimous in the case of recommending *talbot* as a psychophysical correlate of *joule*. The vote on *lumerg* as the psychophysical correlate of the erg was less unanimous. One other name was suggested for (21); this was *lucifer*. This is of Latin origin and means literally *bearer* or *bringer of light* and seemed to some of us a particularly appropriate name for the unit in which to express the quantity of luminous energy or, as it is now sometimes called, quantity of light. However,

As a matter of permanent record and for the benefit of those vitally interested, a report of the committee vote on the terms shown in Table I is given in Table II.

At the present time a wide diversity of usage will be found in the literature of photometry, radiometry, colorimetry, etc. in the case of the names used in reference to quantitative aspects of the reflection, absorption, emission, etc. processes. We refer to such terms as reflection factor, reflection coefficient, reflecting power, and a multitude of others which might be mentioned. This committee feels that single-word terms should be used wherever possible, again agreeing with the report of Dr. Forsythe's committee,[2] and recommends that a terminology as illustrated in Table III be adopted and used generally. The names in column *A* should be used when the quantity referred to applies to a *body* and those in column *B* when the reference is to the *material* itself.

In Fig. 1 an attempt has been made to show in a somewhat schematic fashion the interrelations between the three categories of quantities with which we must deal in a broad and general treatment of color and colorimetrics. These three categories may be designated as physical, psychophysical, and psychical. In the upper part of the chart attention is confined to the intensity aspects of the problem and includes those relationships which are normally considered as constituting the basic foundation of photometry in the narrower sense, that is as dealing only with the evaluation of various aspects of the intensity characteristics of light, its generation, and its use. From the physical point of view, a given sample of radiant energy may be completely specified in terms of a spectral distribution curve, of which the abscissa values are wave-lengths and the ordinates some appropriately chosen intensity specification. The data required to translate such information into terms of the subjective effect produced when that sample of radiant energy acts upon the retina are embodied in the spectral *luminosity* curve shown in the middle column at the top, the ordinates of this curve being lumens per watt plotted against wave-length. If this relationship is known for the particular conditions of the problem, it is then a simple matter to compute various psychophysical correlates of any of the purely physical modes of expressing the intensity aspects of radiant energy. Just below these figures is illustrated one set of terms which are direct correlates of each other, *radiance* (physical), *luminance* (psychophysical), and *brightness* (psychical).

In the lower part of the chart is an analogous illustration covering the extension of these relationships into the field of colorimetrics. Here again a given sample of radiant energy may be completely specified in terms of intensity and wave-length factors. By suitable experimental technic it is possible to determine the curves shown in the middle column. These represent the trichromatic coefficients as function of wave-length. They essentially represent an evaluation of radiant energy in terms of its capacity to evoke hue and saturation as well as brightness. These again are psychophysical relationships and, having been determined either for a given observer or for the average normal observer, it is then possible by a series of mathematical computations to determine for a given sample of energy its ability to evoke color.

The first step in the computation involves a tri-stimulus specification of the color in question, this being expressed in terms of real or imaginary tri-stimulus reference standards. The expression of color in this form is not of maximal psychological significance. In order to give this specification maximal significance, it must be further transformed into quantities that are the psychophysical correlates of the psychological attributes of color as indicated. These are *dominant wave-length*, *colorimetric purity* (or perhaps for convenience in special cases, excitation purity), and *intensity*. The word "intensity" is used at this point in a generalized rather than a specific sense. The most appropriate mode of expressing the "intensity" factor (the psychophysical correlate of brightness) depends upon the particular problem with which we are dealing. For instance, in the case of surfaces viewed by reflected light, the intensity attribute is best expressed in terms of *reflectance*, while if visible by light which is transmitted through the sample in question, the intensity factor may most significantly be expressed in terms of *transmittance*. In other cases, such, for instance, as self-luminous bodies, *luminance* (brightness) may be the most appropriate term. It will be noted that in purely physical terms the stimulus is designated as radiant energy, this radiant energy evaluated in

terms of its capacity to produce color yields *visual energy*, "stimuluscolor," a purely psychophysical entity, and the direct psychophysical correlate of the purely psychical phenomenon, *color*.

We are not at this time presenting the final formulation of the verbal definitions of the quantities shown in Table I, but from the defining equations the manner in which these must be written is quite obvious. However, it may perhaps be well at this time to present a few of the formulated definitions referring to some of the purely subjective terms shown in the last column of Fig. 1.

Sensation (Psychical) Terms

1. Color: Color is the general name for the nonspatial component of the sensation arising from the activity of the retina of the eye and its associated nerve systems.

2. Color attributes: The nature of any color can be completely specified psychologically in terms of three fundamental attributes, this specification taking the form of an immediate description of the color as such *without any reference whatsoever to the stimulus*.

3. Hue: Hue is that attribute of certain colors which permits them to be classed as reddish, greenish, bluish, yellowish, purplish, etc.

4. Classes of colors: Colors may be divided generally into two distinct classes, chromatic and achromatic, depending upon whether they do or do not exhibit hue.

5. Chromatic color: A chromatic color is a color which exhibits hue.

6. Achromatic color: An achromatic color is a color which does not exhibit hue.

7. Brightness (brilliance): Brightness is that attribute of *any* color which permits it to be classified as equivalent to some member of the series of achromatic colors.

8. Saturation: Saturation is that attribute of a chromatic color which determines its *degree* of difference from the achromatic color of the same brightness.

9. Chromaticity: The chromaticity of a color (achromatic color) is determined by the hue and saturation attributes of the color.

The word *value* has been used very extensively in the color field and while the committee has not yet agreed upon a formal definition of the word, it appears that its meaning is most significantly expressed by saying that value is used in reference to relative brightness. It seems quite desirable that some single word should be adopted in lieu of relative brightness, and for this *lightness* has been suggested. Some members of the committee feel quite strongly that lightness is extremely appropriate and meaningful. No final decision on this point has been reached and it will be given further consideration by the committee.

As stated in the beginning, the purpose of publishing this preliminary report is to bring the subject matter to the attention of those vitally interested. The committee will welcome discussion and criticisms, and any communications bearing on this should be addressed to the chairman. Criticisms and suggestions will receive careful consideration and be brought to the attention of the committee for discussion.

Annual Report of the Secretary of the Optical Society of America for the Calendar Year 1936

Membership Record

January 1, 1936 to January 1, 1937

	Honorary	Regular Annual Payment	Regular Life Payment	Associate Individual Annual Payment	Associate Corporation	Total
Membership as of record in the books of the Secretary and Treasurer 1–1–36	4	406	6	190	8	614
Gains during 1936						
By election during 1936 as of 1–1–36	0	0	0	36+	1+	37+
Losses during 1936						
By death	0	2−	1−	1−	0	4−
By resignation as of 1–1–36	0	10−	0	5−	0	15−
Membership as of record 12–31–36	4	394	5	220	9	632
Gains between 12–31–36 and 1–1–37						
By election during 1936 as of 1–1–37	0	0	0	15+	0	15+
By transfer 10–28–36 as of 1–1–37	0	20+	0	0	0	20+
By transfer to regular life membership	0	0	1+	0	0	1+
Losses between 12–31–36 and 1–1–37						
By transfer 10–28–36 as of 1–1–37	0	0	0	20−	0	20−
By transfer to regular life membership	0	1−	0	0	0	1−
By resignation during 1936 as of 12–31–36	0	1−	0	4−	0	5−
By discontinuance of inactive list	0	7−	0	4−	0	11−
By separation for nonpayment of dues	0	6−	0	8−	0	14−
Membership as of record 1–1–37	4	399	6	199	9	617

Elected during 1936 as of January 1, 1936

Robert J. Beitel, Jr. (1032 A)
Alfred Boch (1043 A)
Paul Boeder (1031 A)
Sherwood Fiske Brown (1023 A)
John Chesna (1039 A)
Russell M. Craig (1029 A)
Harry B. Cuthbertson (1021 A)
Merril Distad (1048 A)
Edward E. Free (1065 A)
Alfred N. Goldsmith (1046 A)
Willard P. Greenwood (1028 A)
Ernst A. Hauser (1051 A)
William G. Houskeeper (1038 A)
Andrew Hustrulid (1024 A)
Franklyn C. Hutchings (1026 A)
Edwin H. Land (1045 A)
J. F. Leventhal (1035 A)
Robert R. McMath (1056 A)
W. E. Knowles Middleton (1040 A)
John F. Morrow, Jr. (1034 A)
Julius Neumueller (1030 A)
William F. Peck (1033 A)
Charles Harris Ross (1020 A)
John W. Sage (1052 A)
Edward Robinson Schwarz (1041 A)
Daniel Smith (1037 A)
Spencer Lens Company (1047 AC)
Anthony Sperduto (1036 A)
George Speri Sperti (1025 A)
John Sterner (1042 A)
Russell L. Stimson (1044 A)
Conrad A. Stone (1057 A)
Lewis P. Tabor (1049 A)
William F. Whitmore (1061 A)
Francis Lewis Wurzburg, Jr. (1050 A)
Robert Russell Wylie (1027 A)
Clinton J. T. Young (1022 A)

Elected during 1936 as of January 1, 1937

Reynold E. Ask (1054 A)
Isay A. Balinkin (1070 A)
G. Howard Carragan (1060 A)
R. H. Draeger (1063 A)
Seibert Quimby Duntley (1064 A)
Robert R. Finn (1058 A)
Willem de Groot (1055 A)
Gerald A. Johnson (1062 A)
Wm. Orland Lytle (1068 A)
Nora May Mohler (1059 A)
Rowland S. Potter (1053 A)
Bourdon Francis Scribner (1067 A)
Harvard Burton Vincent (1066 A)
Adrian L. Warntz (1071 A)
Karl S. Weaver (1069 A)

Elected to Regular Membership by Action of the Board of Directors, October 28, 1936, Effective January 1, 1937

Robert J. Beitel, Jr. (1032 R)
Paul Boeder (1031 R)
Lee A. DuBridge (1006 R)
John R. Dunning (845 R)
Alfred N. Goldsmith (1046 R)
George Graham Harvey (975 R)
Geraldine Walker Haupt (1005 R)
Ernst A. Hauser (1051 R)
R. M. Holmes (965 R)
Arthur W. Kenney (934 R)
Edwin H. Land (1045 R)
Roger P. Loveland (1001 R)
Robert R. McMath (1056 R)
J. L. Michaelson (1003 R)
W. E. Knowles Middleton (1040 R)
Nora May Mohler (1059 R)
Charles A. Morrison (982 R)
Gerald Kent Neeland (974 R)
Edward Robinson Schwarz (1041 R)
Conrad A. Stone (1057 R)

Deaths during 1936

E. O. Dieterich (794 R) 4–25–36
William A. E. Drescher (988 A) 12–30–36
Norman Macbeth (17 RC) 9–2–36
Arthur G. Stillhamer (355 RL) 2–5–36

Resignations during 1936 as of January 1, 1936

J. Stiles Beggs (987 A)
Leo Behr (426 R)
Lyman Chalkley, Jr. (935 A)
Henry Crew (62 R)
Melvin Dresbach (471 R)
Gertrude Rand Ferree (159 R)
Elmer A. Harrington (414 R)
E. L. Harrington (768 A)
Seikichi Jimbo (906 A)
C. H. Kerr (14 R)
Harvey B. Lemon (872 R)
W. S. Nelms (850 A)
J. Rud Nielsen (831 R)
Alfred Traeger (430 R)
Frederic A. Woll (664 R)

Resignations during 1936 as of December 31, 1936

L. Willis Bugbee, Jr. (395 R)
Antonius De Graaff (362 A)
Ellis A. Johnson (885 A)
Maurice Ricker (953 A)
George E. Valley, Jr. (980 A)

(*Signed*) L. B. TUCKERMAN, *Secretary*

Annual Report of the Treasurer of the Optical Society of America for the Fiscal Year 1936

CASH TRANSACTIONS JANUARY 1, 1936 TO DECEMBER 31, 1936

Receipts

Dues	$ 4,119.63	
Dues in advance	262.50	
Interest on bonds	697.00	
Interest on Frederic Ives Medal Fund bonds	15.00	
Interest on Adolph Lomb Memorial Fund bonds	32.50	
Interest on bank balance	176.57	
Bank interest on Frederic Ives Medal Fund balance	1.31	
Bank interest on Adolph Lomb Memorial Fund	3.48	
Bank interest on Local Committee Fund	2.78	
Unbudgeted Income	1.00	
Contributions	1,250.00	
	$ 6,561.77	$ 6,561.77

Disbursements

Secretary's expense	$ 639.03	
Secretary's travel expense	75.02	
Treasurer's expense	94.96	
Journal publication expense	1,571.11	
Journal editorial expense	925.00	
R. S. I. subscription expense	858.00	
Contingencies	113.00	
Adolph Lomb Memorial Fund bonds	1,919.06	
Bonds for O. S. A. investment	5,332.28	
	$11,527.46	$11,527.46

Cash decrease January 1 to December 31, 1936		$ 4,965.69
Cash in bank January 1, 1936	$ 9,971.91	
Principal Adolph Lomb Fund, January 1, 1936	2,000.00	
Balance interest Adolph Lomb Fund, January 1, 1936	92.50	
Balance interest Frederic Ives Medal Fund, January 1, 1936	65.71	
Local Committee Fund, January 1, 1936	138.76	
Total cash in bank January 1, 1936	$12,268.88	$12,268.88
Cash in bank December 31, 1936		$ 7,303.19

Frederic Ives Medal Fund

Income

Principal	$500 00
Cash interest balance, January 1, 1936	65.71
Bond interest	15.00
Bank interest on cash balance	1.31
	$582.02

Disbursements

.....	0.00
Balance, December 31, 1936	$582.02

NOTE: The principal $500.00 is invested in U. S. Treasury Certificates which are included in the bonds reported in the accompanying Investment Statement.

Adolph Lomb Memorial Fund

Income

Principal	$2,000.00
Accrued bank interest on principal January 1, 1936	92.50
Accrued bank and bond interest December 31, 1936	33.81
	$2,126.31

Disbursements

$2000 Dominion of Canada 3¼% bonds including commissions, taxes and fees	$1,919.06
Balance interest and remaining capital on December 31, 1936	$ 207.25

NOTE: The $1919.06 part of the principal is invested in Dominion of Canada 3¼% bonds which are included in the bonds reported in the accompanying Investment Statement.

Local Committee Fund

Income

Balance January 1, 1936	$138.76
Bank interest	2.78
	$141.54

Disbursements

.....	0.00
Balance December 31, 1936	$141.54

Optical Society Investments

	Cost	Dec. 14, 1936 Market Value
Bonds		
$7000 Atchison Topeka & Sante Fe 4%	$ 6,916.25	$ 8,207.50
5600 U. S. Treasury Certificates 3¼%	5,625.67	6,188.00
8000 U. S. Treasury Certificates 3%	8,261.30	8,584.80
2000 Dominion of Canada 3¼%	1,919.06	2,072.50
Stocks		
10 shares Eastman Kodak Common	1,731.40	1,750.00
40 shares General Electric Common	1,871.35	2,090.00
30 shares Kennecott Copper Corp. Common	1,929.53	2,126.25
	$28,254.56	$31,019.05

NOTES: 1. $500.00 of the $8,000 U. S. Treasury 3% Certificates represent the invested principal of the Frederic Ives Medal Fund.

2. The $2,000 Dominion of Canada 3¼% bonds represent the invested principal of the Adolph Lomb Memorial Fund.

(*Signed*) HENRY F. KURTZ, *Treasurer*

February 23, 1937

The undersigned, having been duly appointed to audit the books of the treasurer of the Optical Society of America, Inc., from January 1, 1936 to December 1, 1936, hereby certify that the treasurer's report of receipts, disbursements and investments is correct as shown by records, vouchers, bank statements, etc.

(*Signed*) CARL L. BAUSCH, C. W. FREDERICK, *Auditors*

Report of the Editor of Publications

STATEMENT OF OPERATIONS OF THE JOURNAL OF THE OPTICAL SOCIETY OF AMERICA FOR THE YEAR ENDING DECEMBER 31, 1936

A. In Account with American Institute of Physics Inc.

Income

Subscriptions		$3,740.89	
Net Income from published articles (Schedule 1)		921.60	
Net Income from single copies (Schedule 1)		663.19	
Miscellaneous		13.85	$5,339.53

Expenses

Printing and mailing		$4,975.07	
Editorial expenses (A. I. P. office)			
Salaries	$530.46		
Office expenses	168.79	699.25	
Business management expenses			
Salaries	507.42		
Office expenses	227.74	735.16	
Miscellaneous		6.89	
Total expenses			$6,416.37
Excess of expense over income			$1,076.84
Service charge of American Institute of Physics			1,115.67
Net cost of editorial mechanics, printing and distributing journal			$2,192.51

B. Expenses in editorial office (Ithaca)

Salaries		$1,000.00	
Miscellaneous		81.24	
Total in Ithaca office			$1,081.24
Total net cost of journal for 1936			$3,273.75

* * * *

Number of pages published	1936	1935	1934	1933
Text and index	460	426	355	436
Covers and front matter	82	78	80	78
Total	542	504	435	514

Cumulative Index of the Journal of the Optical Society of America

Cost of Printing and Mailing		$1,051.44
Editorial Expense (in A. I. P. office)		
Salaries	$ 135.80	
Office expense	39.20	175.00
Total cost		$1,226.44
Service charge of American Institute of Physics		183.96
Total Cost to the Optical Society of America		$1,410.40
Deduct sales of single copies		100.00
Net cost to December 31, 1936		$1,310.40

SCHEDULE 1

Net Income from Published Articles

Income		
"Per Page" publication charges	$1,278.05	
Sales of reprints	530.52	$1,808.57
Expense		
Manufacture and mailing of reprints	$ 752.55	
Business management salaries	104.42	
Business management office expense	30.00	886.97
Net Income from published articles		$ 921.60

Net Income from Sales of Single Copies

Income—Sales of Single Copies		$ 797.62
Expense		
Business management salaries	$ 104.43	
Business management office expense	30.00	134.43
Net Income from sales of single copies		$ 663.19

(*Signed*) F. K. RICHTMYER, *Editor*

Proceedings of the Spring Meeting of the Optical Society of America

CORNING, NEW YORK
March 5–6, 1937

THE spring meeting of the Optical Society of America was held at Corning, New York, March 5 and 6, 1937. The meeting was opened Friday morning, March 5 at 9:15 A.M. by Vice President Gibbs introducing H. P. Gage who welcomed the society on behalf of the Corning members.

SESSIONS FOR THE READING AND DISCUSSION OF CONTRIBUTED PAPERS

Sessions for the reading and discussion of contributed papers were held on Friday, March 5, at 9:30 A.M. and Saturday, March 6, at 9:00 A.M. The authors' abstracts of these papers are appended.

COMPLIMENTARY LUNCHEON BY CORNING GLASS WORKS

The Corning Glass Works entertained the members of the society and its guests with a complimentary luncheon Friday noon.

VISITS TO PLANTS OF THE CORNING GLASS WORKS

The plant at Wellsboro, Pennsylvania was open to visitors of the Optical Society all day on Thursday, March 4. Visitors were shown the manufacture of electric light bulbs by high speed automatic machinery.

On Friday afternoon the members of the society and its guests were assembled in small groups with guides and conducted through the main plant where they were shown the varied operations of manufacture of glassware, largely by hand.

On Satuday afternoon a similar visit was made to the Fall Brook Division, where the automatic drawing of glass tubing was shown, and to the Fiber Products Division, which specializes in the manufacture of fine glass fibers for insulating materials and other uses.

On Saturday morning a special demonstration for the ladies was given by the Pyrex Sales Division and the Art Ware Division.

INFORMAL DINNER AND DEMONSTRATION OF PHOTOELASTIC PHENOMENA

The informal dinner Friday evening, with President Arthur C. Hardy presiding, was followed by a demonstration by Guy Stong of the Corning Glass Works of some of the remarkable effects of strain in glass and its detection and measurement by means of polarized light.

VOTE OF THANKS

At the close of the session Saturday morning, W. B. Rayton moved a vote of thanks to the Corning Glass Works, the Corning Chamber of Commerce and the members of the local committee for their hospitality and the many courtesies which had contributed to a highly successful and enjoyable meeting. The motion was carried unanimously and the Secretary was instructed to write to them, expressing the thanks of the Society.

REGISTRATION

Members 50: Guests 79: Total 129.

MEETING OF THE BOARD OF DIRECTORS

A meeting of the Board of Directors was held on Thursday, March 4, 1937. Minutes of the meeting are appended.

L. B. TUCKERMAN, *Secretary*

Minutes of the Ninth Meeting of the Directors of the Optical Society of America, Incorporated

CORNING, NEW YORK
MARCH 4, 1937

BESIDES the transaction of routine business, the following items of general interest to members of the society were taken up:

Announcements by Secretary

1. Appointment and confirmation by letter ballot November 25, 1936 of A. C. Hardy and L. A. Jones as additional representatives of the Optical Society of America on the U. S. National Committee of the International Commission on Illumination.

2. Appointment of F. K. Richtmyer and W. B. Rayton proxies for the Optical Society of America, Incorporated at the annual meeting of that corporation held in New York City, February 27, 1937.

Appointments by President, confirmed by the Directors

1. Nominating committee

W. B. RAYTON, *Chairman*

WALTER CLARK	G. B. PEGRAM
A. W. KENNEY	A. G. WORTHING

2. Committee on transfer from associate to regular membership

W. E. FORSYTHE, *Chairman*

H. E. IVES	W. B. RAYTON

3. Committee to consider the editorial policy of the journal

F. K. RICHTMYER, *Chairman*

G. R. HARRISON	L. A. JONES
H. E. IVES	L. W. MCKEEHAN

4. Frederic Ives Medal committee for 1937

G. R. HARRISON, *Chairman*

K. K. DARROW	C. W. KEUFFEL
W. E. FORSYTHE	BRIAN O'BRIEN

Representative on the Division of Physical Sciences of the National Research Council

The nomination of W. E. Forsythe for the term July 1, 1937 to June 30, 1940 was approved.

Delegates to 100th meeting of the American Association for the Advancement of Science to be held in Denver, June 21–27, 1937

The President was authorized to appoint delegates to represent the Optical Society of America at the meeting.

Transfer of editorial responsibility for The Review of Scientific Instruments

When the ownership in *The Review of Scientific Instruments* was transferred to the American Institute of Physics, by the contract signed October 20, 1932, the Optical Society agreed to continue to cooperate in the editorial management of *The Review*. There being no longer need for this cooperation, the Directors voted to authorize the annulment of the clauses containing that agreement and to transfer all responsibility for editing *The Review* to the American Institute of Physics.

Annual Meeting

It was voted that the annual meeting of the Society be held at the Lake Placid Club, October 14, 15 and 16, 1937.

(*Signed*) L. B. TUCKERMAN, *Secretary*

Program of Sessions for Contributed Papers

Titles and Abstracts of Papers

1. Changes in the Atomic Arrangement of Glass During Cooling.* Howard R. Lillie, *Corning Glass Works.* (Introduced by H. P. Gage.) (30 minutes.)

A true glass apparently consists of a network of atoms, the randomness of which depends upon the intensity of thermal agitation. Atom bonds are quite distorted at all temperatures, their regularity never being of such an order as to constitute crystallites. During cooling, the decrease in thermal agitation allows the atoms to approach statistically their desired positions. The viscosity partly determines the speed of this approach, the required rearrangement taking place rapidly at high temperatures but slowly at low temperatures. A certain temperature, depending upon the cooling rate, will appear, above which the lag between temperature and atomic rearrangement is negligible and below which the lag is appreciable. This critical temperature is usually in the annealing range. Heat treatment at any temperature below the critical one must cause a progressive change in physical properties as the atoms approach nearer to the ultimate statistical equilibrium condition determined by that temperature. Changes in such properties as refractive index, density, expansion coefficient, electrical conductivity, elastic modulus, and viscosity are shown. These properties indicate that the temperature uniquely determines the final state, which is approached from one direction or the other depending on previous thermal history. Extended viscosity tests made by fiber elongation and stress release tests made by optical methods are described. Results indicate that if we take into account the variation of viscosity with time at constant temperature, then the rate of stress decrease is proportional to the first power of the stress rather than to the second power as concluded by Adams and Williamson[1] who assumed that the physical properties were constant.

* The present paper will appear in full in the J. O. S. A.
[1] L. H. Adams and E. D. Williamson, "The Annealing of Glass," J. Frank. Inst. **190**, 597–631, 835–870 (1920).

2. The Effect of Heat Treatment on the Refractive Index of Glass. A. Q. Tool, L. W. Tilton and J. B. Saunders, *National Bureau of Standards.* (10 minutes.)

In a paper read[1] at the Ithaca meeting of the Optical Society of America in 1925 it was shown that the index of refraction of glass as determined under the usual standard conditions can be increased by lowering the annealing temperature, and can also be decreased correspondingly by raising that temperature. Since that time the investigation has been extended to a number of glasses, and the changes obtained in the indices per degree Centigrade change in the annealing temperature have in part been published in the annual reports of the Director of the National Bureau of Standards. Meanwhile Lebedeff,[2] Stozarov,[3] and others have been pursuing similar investigations. Stozarov, in particular, investigated several optical glasses and has shown by series of index determinations made without breaking the annealing process how the index slowly approaches definite values which vary with the annealing temperature. The glasses investigated at the National Bureau of Standards include not only the optical glasses currently produced there but also eight of its earlier melts for which optical data and batch compositions are published in the Smithsonian Physical Tables (p. 358, 8th ed.). Tentative results for the sensitivity of refractive index to annealing temperature have been obtained from index measurements made on these glasses at 25°C. For sodium light these sensitivities (per 1°C) multiplied by 10^6 are 2.9, 5.5, 3.0, 4.4, 2.6, 5.5, 2.7, and 3.0, respectively, for the melts 103 (123), 241, 135, 116, 188, 151, 163, and 76. In three cases (melts 151, 163, and 123) the original prisms used in obtaining the data in the Smithsonian Tables were not available. Duplicate samples of the first two were obtained but there was some indication that the optical properties had not been uniform throughout melt 163. No sample of melt 123 was found. In its stead one from melt 103 which had about the same batch composition and production date was tested.

[1] Tool, Tilton, and Hill, J. O. S. A. and R. S. I. **12**, 490 (1926).
[2] A. A. Lebedeff, Revue d'Optique **5**, 1 (1926); Die Glas Industrie **35**, 6 (1927).
[3] A. I. Stozarov, Trans. Opt. Inst., Leningrad, **4** (No. 39), 1–36 (1928).

3. Optical Problems in the Large. M. Herzberger, *Kodak Research Laboratories.* (15 minutes.)

The introduction of the natural and the diapoint variables has simplified considerably the investigation of problems in the large, problems where we can give the eiconal in closed form, and therefore for each object ray the image ray. The author and H. Boegehold have, first together and then alone, investigated problems of this kind. The author first sketches once more his new method, and then gives a series of examples, such as the eiconal for the case where to each object point belongs a rotation symmetric caustic, the eiconal for sharp image formation of two surfaces, the eiconal in the case where there is perfect centric symmetry, and other examples which are discussed as far as the time limit permits.

4. Orthostereoscopy.* Henry F. Kurtz, *Bausch & Lomb Optical Company Scientific Bureau.* (20 minutes.)

The group of equations for camera and the stereoscope for the establishment of orthostereoscopy set forth before this society at the October 1927 meeting will be reviewed. The special cases of unit magnification for both the camera and stereoscope systems with normal viewing distance both short, of the order of 15 inches, and very long will be discussed. The cases for magnifications less than unity with short normal viewing distances and for very high magnifications with short normal viewing distances will be touched upon. The character of the image space of binocular telescopes will be discussed, leading to the conclusion that the

only binocular telescope that presents an orthostereoscopic view is one of unit power with telescope axes separated by the interocular distance. A criterion for the determination of whether or not any particular camera and stereoscope system or binocular observation system can present orthostereoscopic views to the observer will be discussed. The multiplex projector used in aerial mapping will be considered from the standpoint of orthostereoscopy.

* The present paper will appear in full in J. O. S. A.

5. An Examination of the Principles of Orthostereoscopic Photomicrography and Some Applications. L. C. MARTIN AND T. R. WILKINS, *Institute of Optics, University of Rochester.* (20 minutes.)

The object of producing stereoscopic pictures of alpha-ray and other tracks in photographic emulsions of which a preliminary account was given by one of us[1] has led to an examination of the conditions necessary for orthostereoscopic reconstruction of the space-image, produced by pairs of photomicrographic perspectives, in the sense of an enlarged true-to-scale model of the object. Such conditions have already been worked out by H. F. Kurtz for the case of images of moderate magnifications projected by a simple lens system. It is suggested in the present paper that the requisite perspectives can be obtained for higher magnifications from a compound microscope with the aid of an internal stop so placed that its images formed by the objective and eyepiece, respectively, correspond with the nodal points of the compound microscope. The object is moved on the stage a requisite interval between the two exposures. For magnifications of 900× a typical stage shift is 0.03 mm.

Examples of orthostereoscopic reconstruction are given in the case of ray tracks. In the case of opaque objects the perspective is hypercentric, but in view of the small depth of focus the image is usually indistinguishable from a true reconstruction.

Particulars are given of a stereoscope equipped with a protractor for the measurement of the spatial angles of the reconstructed tracks. In the case of ray tracks in a photographic emulsion adjustment is made for the refractive index of the gelatine.

[1] T. R. Wilkins, Phys. Rev. **49**, 639 (1936).

6. Graphical Exposition of the Michelson-Morley Experiment.* HERBERT E. IVES, *Bell Telephone Laboratories.* (20 minutes.)

The progress of a light pulse through the Michelson-Morley apparatus is followed by graphical plotting of the Huygens' construction for a large value of velocity. A plot of the results for all orientations of the apparatus illustrates the production of two emergent pulses inclined to each other by the square of the aberration angle. Introduction of the Fitzgerald-Lorentz contraction brings the two emergent pulses together, but the single resultant pulse leaves the apparatus for certain orientations at the aberration angle, this constituting an outstanding difference between the moving and stationary cases. It is pointed out that the Kennedy-Thorndyke modification of the Michelson-Morley experiment can be explained by a contraction of the apparatus in both directions, without calling upon a change of clock frequency.

* The present paper will appear in full in J. O. S. A.

7. The Optical Constants of Sodium.* HERBERT E. IVES AND H. B. BRIGGS, *Bell Telephone Laboratories.* (15 minutes.)

Optical constants of sodium through the visible and ultraviolet portions of the spectrum have been obtained by the photographic method previously used for potassium.[1] A different method for preparing the alkali metal surface for observation has been used. The metal is deposited on a flattened glass bulb in the center of a tube furnished with quartz windows. By careful annealing the sodium layer a specular surface is obtained, permitting measurements on the free metal in vacuum.

* The present paper will appear in full in J. O. S. A.
[1] J. O. S. A. **26**, 238 (1936).

8. A Study of the Effect of Exposure to Radium upon the Triboluminescence of Certain Natural Crystals and Synthetically Prepared Materials.* FRANCES G. WICK, *Vassar College.* (10 minutes.)

The work described in this paper was done at the Institute for Radium Research in Vienna through the courtesy of Dr. Stefan Meyer and Professor Karl Przibram. Previous observations have shown that the triboluminescence of some natural crystals such as fluorite and rock salt is greatly intensified by exposure to radium or x-rays. This triboluminescence is easily observable when the crystals are crushed in a vice or ground in a mortar. Visual spectroscopic observations of the triboluminescence of twelve specimens of fluorite from widely different sources show the narrow bands characteristic of the rare earths, most strongly those of Dy and Tb. These same bands appear in the phosphorescence and the thermoluminescence of these crystals after exposure to radium.

Fluorite crystals after subjection to the heat of the blast still show triboluminescence with spectra showing the rare earth bands which are not the same in different crystals. Synthetic materials containing CaF_2 and known quantities of rare earths showed triboluminescence similar, in every respect to that of natural fluorite. Both the natural and synthetic materials showed tribothermoluminescence. Observations were made upon a number of other natural crystals including calcite, apatite, chalcedony, rock salt, feldspar and quartz and upon other synthetically prepared materials including ZnS, $CaWO_4$, and $CdWO_4$.

The results of the observations indicate that, in the emission of triboluminescence there are three distinct factors, one or more of which may take part in the triboluminescence of any given substance. (a) Emission from unstable, excited centers activated by exposure to radium, x-rays or cathode rays closely resembling phosphorescence and moderately low temperature thermoluminescence. (b) Emission from stable, heat resistant centers characteristic of the material not dependent upon any external

excitation except the mechanical breaking or crushing of the material. (c) Electric discharge in the air.

The principle of identity of luminescence spectra regardless of the source of excitation applies to triboluminescence. The rare earth bands in the spectra of fluorites make comparison easy.

* The present paper will appear in full in Sitz. Akad. Wiss. Wien, Mitteilungen des Institutes für Radiumforschung. A paper on this subject will also be submitted for publication in the J. O. S. A.

9. Further Study of the Reversible Photosensitivity in Hackmanite from Bancroft, Ontario.* O. IVAN LEE, *Jersey City, N. J.* (Introduced by H. P. Gage.) (20 minutes.)

Sodalite, variety, hackmanite, $3Na_2O.3Al_2O_3.6SiO_2.2NaCl$, found in the Americas only near Bancroft, Hastings county, Ontario, exhibits an extraordinary color transformation on brief exposure to any convenient ultraviolet source, including the argon bulb, iron spark, carbon arc with cored carbons, quartz tube mercury vapor lamp, and daylight or artificial light screened through a Corning Corex A Red Purple No. 986 filter. The color is progressively intensified from colorless through red violet to purple, the rate of color change and hue attained depending on the nature, intensity and time of exciting radiation, usually requiring only a few seconds. Interposition of calibrated selective filters determined the radiaton responsible as not longer than about 4800A, but probably extending down to about 2250A or even lower. The induced color slowly fades in darkness to bright red violet in 24 hours, no visible change occurring thereafter. On exposure to strong light, the color is bleached rapidly and completely, the reversing radiation having a peak in the visible region in wave-lengths shorter than yellow (green?) although extending to 7500A, longer wave-lengths up to 39,000A having no effect. Intensification and reversal may be repeated indefinitely, and is attributed to the known presence of a trace of manganese, spectrographic analysis disclosing 0.001 percent, as well as the extraneous elements Li, Ga, Pb and Nd, and traces of Be, Ba, Sr and perhaps P, some of which are suspected involved in either the photosensitivity or luminescent properties or both. A solution of $MnSO_4$ containing 0.001 percent Mn when oxidized by sodium bismuthate yields a permanganate color whose hue and intensity closely resembles that developed by the mineral. Examination of a thin colored section failed to reveal the absorption bands in the green characteristic of H_2MnO_4 salts in aqueous solution. The hackmanite fluoresces salmon and phosphoresces sky blue, but colorless associated minerals phosphoresce various colors or not at all. Heating causes a strong green phosphorescence, but destroys photosensitivity and further thermoluminescence. Both the partial recovery of color in darkness following reversal (hitherto inexplicable) and the partial reversal following excitation are suggested as due to concomitant phosphorescence having compound radiations, visible and invisible.

* O. Ivan Lee, "A New Property of Matter: Reversible Photosensitivity in Hackmanite from Bancroft, Ontario," Am. Mineralogist **21**, 764–776 (1936) with additional experimental data herewith presented.

10. Water Vapor in the Construction of More Sensitive Photoelectric Cells of Alkali Metals.* JAKOB KUNZ, *University of Illinois.* (10 minutes.) Read by title.

It was found that purest hydrogen, having passed through a palladium cylinder, did not increase the photoelectric sensitiveness of alkali surfaces when ionized by a sufficiently high potential difference, but ordinary hydrogen, of course, increases the sensitiveness many times and the effect must therefore be attributed to an impurity, especially to oxygen or water vapor. We prepared, therefore, photo-cells with hydrogen that had bubbled through a thin layer of vapor nearly at freezing temperature and found a very marked increase in the sensitiveness over that obtained with ordinary hydrogen. Moreover, the color of the sensitive alkali layer was darker blue and rose-violet than the colors obtained before. After the cell had been sensitized by wet hydrogen, this gas was pumped out completely with a mercury-vapor pump. After a few seconds, gas began to develop from the walls of the cell, the color changed slightly and the sensitiveness decreased gradually to about half of its initial value, but it remained still about five times higher than that obtained without water vapor. We are trying the effect of oxygen also.

* The present paper will appear in full in J. O. S. A.

11. The Experimental Determination of Photographic Density.* A. M. KOERNER AND CLIFTON TUTTLE, *Eastman Kodak Company.* (15 minutes.)

The fact that various instruments used to determine photographic density yield different results makes it desirable that some one method should be chosen as a standard. This method should produce results which are in keeping with the implications of the Hurter and Driffield definition[1] of photographic density. A study has been made, extending some of the previous work of Tuttle,[2] of the factors responsible for discrepancies between the readings of existing densitometers, and it is concluded that the integrating sphere densitometer[3] is best suited to serve as a standard instrument. The relations existing between its readings and those of other densitometers are given and it is shown that these relations are valid for a wide range of photographic materials of varying grain size. Toy's[4] experiments to determine contact printing densities have been repeated with somewhat different results. Certain effects connected with opal densitometers and reported by Bull and Cartwright[5] have been explained. The dependence of photographic density upon orientation of the photographic sample, that is, whether the emulsion side or base side acts as first surface, is shown. Thin metallic films on glass have been suggested to serve as standard densities. It is shown that such films are not suitable for this purpose since their optical properties are quite different from those of the photographic density.

* The present paper will appear in full in J. O. S. A.
[1] F. Hurter and V. C. Driffield, J. Soc. Chem. Ind. **9**, 455 (1890).
[2] Clifton Tuttle, J. O. S. A. **24**, 272 (1934).
[3] Enoch Karrer, J. O. S. A. **5**, 96 (1921).
[4] F. C. Toy, Phot. J. **49**, 164 (1925).
[5] A. J. Bull and H. H. Cartwright, Phot. J. **49**, 177 (1925).

12. Problems in the Development of a Multiple-Purpose Reflectometer. RICHARD S. HUNTER, *National Bureau of Standards and George Washington University.* (20 minutes.)

A null-method reflectometer[1] employing a pair of blocking-layer photo-cells in series circuit to measure normal−45° apparent reflectance was described by the author at the October, 1935 meeting of the Optical Society. The null method enabled the instrument to operate directly from line voltages and because the simple blocking-layer photo-cell circuit provided good sensitivity, the instrument proved to be well suited to the handling of a number of reflectance problems. Since the completion of this earlier instrument, however, a number of problems have arisen, the solution of which would seem to require modification of the first design. Thus, for instance, the Technical Research Section of the Porcelain Enamel Institute, which was in part responsible for the development of the previous apparatus, desires the development of a null-method, blocking-layer photo-cell instrument to measure specular gloss in addition to normal−45° apparent reflectance. Furthermore, Gibson[2] has recently pointed out certain principles underlying the proper design of photoelectric instruments intended for colorimetric measurements. A number of users of the previous apparatus have complained that it does not make such measurements conveniently or accurately. To other users, the losses of precision due to heating effects within the instrument have proved troublesome.

It has been the purpose of the present research to develop a null-method, blocking-layer photo-cell device which is (1) capable of measuring specular gloss, contrast gloss, sheen and bloom[3] as well as 45°−normal apparent reflectance, (2) capable of making colorimetric measurements suitable for identifying small color differences, and (3) constructed so as to eliminate troublesome temperature and fatigue effects of the photo-cells. An instrument for this purpose has now been designed. Light from a stationary source, after passage through a spectral filter, is divided into two beams. One beam is incident at 45° upon a surface which is viewed normally by one of the photo-cells. Motion toward and away from this surface varies the illumination upon this photo-cell and provides a means for compensating for differences in the apparent reflectances of various surfaces. This variation in illumination follows approximately an inverse square relationship and the apparent reflectance scales have been prepared, checked experimentally and mounted in the instrument to move with this photo-cell.

The second beam is small and is taken from the center of the main beam by means of a small mirror. It is directed to the second surface at 45°. That part of the light which is reflected at −45° is directed to the stationary gloss photo-cell. When 45°−normal apparent reflectance is being measured, the 45°−45° beam is used as the comparison beam and a comparison sample is left in the "gloss position." On the other hand, when gloss is being measured, a comparison sample is left in the "45°−normal position."

Problems in the optical and mechanical design of the apparatus will be discussed. The characteristics of a number of photo-cells have been examined for possible use in the apparatus. Problems to be considered in the adaptation of the apparatus for colorimetric measurements will be noted.

[1] R. S. Hunter, J. O. S. A. **26**, 225 (1936).
[2] National Bureau of Standards Letter Circular LC-473 (July 9, 1936).
[3] R. S. Hunter, Methods of Determining Gloss, Nat. Bur. Stand. J. Research **18**, 19 (1937); (RP958).

13. Note on Choice of Apertures in the Definitions of Specular Gloss and Contrast Gloss. DEANE B. JUDD, *National Bureau of Standards.* (15 minutes.)

The ideas of specular reflection and diffuse reflection as distinct processes have long been used in discussions of gloss, but no rigorous definitions of specular reflectance and diffuse reflectance as ratios of reflected to incident light have been given. Indeed, for ordinary objects such rigorous definitions are not possible because it is, in general, impossible to separate the portion of the reflected light which has penetrated the first surface of the object from that which has not. However, these definitions are stated in the present paper for hypothetical perfectly polished objects (ideal mirror, ideal polished black glass, ideal polished white glass) and for other hypothetical objects (ideal perfectly reflecting, perfectly diffusing surface, ideal matt black surface). For these hypothetical objects, the relationship of apparent reflectance to specular and diffuse reflectance is derived and shown to depend upon angular size of source and viewing element. This dependence has previously been largely if not completely overlooked. The relationship derived is in turn applied to the usual definitions of specular ("objective") gloss and contrast ("subjective") gloss.[1] Specular gloss is defined as the ratio of apparent reflectance of the sample in the direction of mirror reflection to that for a standard (such as polished black glass) in the same direction. It has the useful property of remaining constant for surfaces that are physically similar regardless of the light-absorbing characteristics of the material beneath, and on this account has sometimes been called objective gloss. Contrast gloss is supposed to have the property of remaining reasonably constant for objects that appear equally glossy, and on this account has sometimes been called subjective gloss. By a consideration of the hypothetical surfaces which alone give definite meaning to the terms, specular and diffuse reflectance, it is shown that the conditions governing choice of sizes of source and viewing element are quite dissimilar for these two types of gloss. If the sizes are made quite small, specular gloss retains its characteristic property, but contrast gloss does not. Much larger source or viewing-element sizes are suggested for measurement of contrast gloss than are now used.

The theoretical treatment has been simplified by expressing the angular apertures as fractions of the sphere tangent to the sample instead of in steradians or as fractions of the hemisphere, which are more usual methods.

This method of specification also simplifies computation of the correction for "diffuse" reflection in measurement of specular gloss.

[1] R. S. Hunter, Nat. Bur. Stand. J. Research **18**, 19 (1937); (RP958).

14. Rectangular Uniform-Chromaticity-Scale Coordinates. F. C. BRECKENRIDGE AND W. R. SCHAUB, *National Bureau of Standards.* (20 minutes.)

The advantages and limitations of the I.C.I. coordinate system[1] and the trilinear coordinate system yielding uniform chromaticity scales as proposed by Judd[2] are compared. The advantages for engineering applications of a system combining the rectangular coordinates with the uniform chromaticity scale (UCS) are pointed out and the UCS triangle is transformed to give such a system. A slight modification of the constants and simple translation gives a system of coordinates in which the first quadrant contains only greens, the second reds and yellows, the third purples and the fourth blues. The distribution coefficients for an equal energy spectrum and for the spectrum of a Planckian radiator at 2842°K are given and also the ordinates to be used in computing chromaticity coordinates by the Hardy selected ordinate method[3] for a source of 2842°K. A diagram containing small areas illuminated with the appropriate colors will be shown.

[1] D. B. Judd, "The 1931 I. C. I. Standard Observer and Coordinate System for Colorimetry," J. O. S. A. **23**, 359 (1933).
[2] D. B. Judd, "A Maxwell Triangle Yielding Uniform Chromaticity Scales," J. O. S. A. **25**, 24 (1935).
[3] Arthur C. Hardy, "The Computation of Trichromatic Excitation Values by the Selected Ordinate Method," J. O. S. A. **22**, 430 (1932). Also *Handbook of Colorimetry*, p. 49.

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